INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

RESEARCH ARTICLE

OPEN ACCESS

Received: 29-01-2024

Accepted: 14-03-2024

Published: 04-04-2024

Citation: Singh KK (2024) Land Surface Temperature and Thermal Comfort in the Cities of Punjab, India: Assessment Based on Remote Sensing Data. Indian Journal of Science and Technology 17(15): 1535-1544. https://doi.org/10.17485/IJST/v17i15.228

* **Corresponding author**.

kiran.singhgeo@gmail.com; ksingh@allduniv.ac.in

Funding: None

Competing Interests: None

Published By Indian Society for Education and Environment (iSee)

ISSN
Print: 0974-6846
Electronic: 0974-5645

Land Surface Temperature and Thermal Comfort in the Cities of Punjab, India: Assessment Based on Remote Sensing Data

Kiran Kumari Singh[1]*

1 Department of Geography, University of Allahabad, Prayagraj, Uttar Pradesh, India

Abstract

Objective: The present study aims to investigate thermal comfort in two cities in Punjab, India based on land surface temperature (LST), urban hot spots (UHS) and urban thermal field variance index (UTFVI). **Method:** Landsat 8 OLI/TIRS data are used to derive land surface temperature (LST), normalized difference vegetation index (NDVI) and enhanced built-up and bareness index (EBBI) for the year 2019. UTFVI reflects urban thermal conditions and demarcates comfort and discomfort zones in the cities. **Findings:** The results revealed that the mean LST (μ) of Ludhiana and Amritsar cities is 32.80 °C and 30.70 °C, respectively. LST shows a strong negative correlation with NDVI (-0.710 for Amritsar and -0.754 for Ludhiana) and a positive correlation with EBBI (0.531 for Amritsar and 0.541 for Ludhiana). About 57 and 52 per cent of geographical areas in Ludhiana and Amritsar city respectively are experiencing bad to worst ecological conditions. **Novelty**: (i) The study derived LST-based thermal comfort for the summer month in Amritsar and Ludhiana cities of Punjab which provide important information to urban planners and policymakers to design sustainable urban development policies to mitigate heat-related issues. (ii) Such information can be used to take steps to improve the situation in smart cities like Amritsar and Ludhiana.

Keywords: Land surface temperature (LST); urban thermal field variance index (UTFVI); NDVI; Landsat 8; Punjab

1 Introduction

Cities are major contributors to climate change due to their population density, economic growth potential[1], infrastructure development, consumption of resources and greenhouse gas emissions[2]. Urbanization induced development has modified the environment on a large scale and this is most notable in terms of land use/land cover (LULC) changes. Urbanisation process has caused destruction of urban vegetation, green cover, water bodies and open spaces[3] and increased artificial impervious surface[4]. This has led to the modification in thermal environment of the cities[5]. Rising heat in urban areas has become a matter of concern due to its adverse impact on thermal comfort in cities[6,7]. UHI (Urban Heat Island) is a phenomenon when the ambient temperature at certain urban locations is higher than the non-urban or adjoining areas [8]. One of the key parameters for analysing the microclimate or UHI of urban areas is the land surface temperature (LST) which reflects the thermal behaviour of the earth's surface and is influences by the extent of urbanization. A considerable amount of literature has investigated the impact of urbanisation and land use change on increasing values of land surface temperatures (LST) [9] and local microclimate in the Indian cities [10].

Though some earlier studies have examined the status of UHI in cities of Punjab, such as the impact of urban sprawl on LST in Ludhiana city [11],LST based thermal comfort in Ludhiana, Bathinda and Balachaur cities [12]. They have not investigated the spatial patterns of LST and thermal comfort during summer months in Ludhiana and Amritsar cities of Punjab. Understanding LST and hot spot dynamics in different seasons is important for land use planning and developing effective climate change adaptation strategies. Furthermore, this study used EBBI to separate built-up and barren surfaces to analyse the impact of these two LULC classes on LST behaviour thereby reducing the effort of calculating multiple indices to distinguish between these two classes. Apart from this, there is no such study for Amritsar city, which has been selected under the Smart City Mission project.

In light of the above concerns and research gaps, the present study has selected Ludhiana and Amritsar cities from the state of Punjab, India to study LST based urban hot spots (UHS) and thermal comfort for summer months using geospatial techniques. This study provides some useful information to urban planners and policy makers to do something to improve the situation in terms of Sustainable Development Goal 11.

2 Study area

Ludhiana, the largest city of Punjab, is located at 30°54′ north latitude and 75°51′ east longitude and has emerged as a centre of economic and industrial activity in North India. Unplanned development and resultant sprawl have created various environmental problems in the city. The city of Amritsar (the second largest city of Punjab), located at 31°38' north latitude and 74°52' east longitude, is a religious and tourist centre of the state. These two locations are shown in Figure 1.

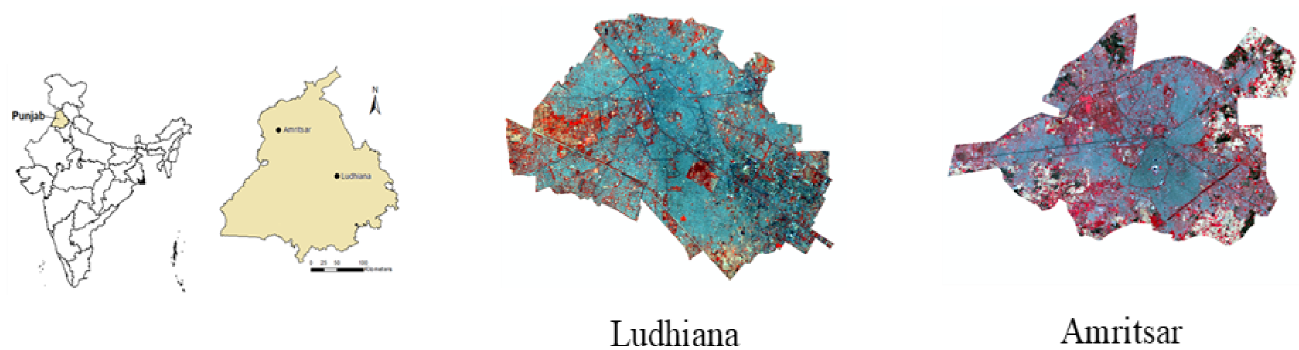


Fig 1. Location of the study area (as shown in Landsat 8 data of May 2019)

3 Methodology

3.1 Data sources

GIS and remote sensing techniques have augmented the capacity to understand urban thermal behaviour [13]. Thermal bands of satellite data have been widely used to study LST as a proxy of the surface urban heat island. It has an advantage over air temperature data recorded at weather station due to free and frequent availability. The lack of urban weather stations has led researchers to opt for satellite data to gather empirical evidence on LST [14]. The present study has used Landsat-8 OLI-TIRS remote sensing imagery for the year 2019 to obtain NDVI, EBBI and LST in the selected cities. The satellite data are freely available for research and academic work on http://www.earthexplorer.usgs.gov (US Geological Survey, USA). Landsat-8 satellite has two sensors, i.e. OLI and TIRS. High-resolution Google Earth data is used as the reference data for validation of result and identification of UHS. Table 1 shows the specifications of the data used in this study.

Table 1. Landsat 8 OLI and TIRS data specification

Cities	Path/row	Date of acquisition	Sun elevation	Sun azimuth
Ludhiana	148/039	12 May 2019	67.09	117.42
Amritsar	148/038	12 May 2019	66.60	120.78

3.2 Normalized Difference Vegetation Index (NDVI)

NDVI (Normalized Difference Vegetation Index) is a useful method to extract vegetation cover information from the land surface[15]. Theoretically, the value of NDVI ranges from –1 to +1, where negative values indicate water features; the 0 value indicates bare soil while the positive value indicates vegetation cover. The formula for NDVI is as follows:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \tag{1}$$

NIR represents the reflectance of the near infrared band and Red represents reflectance in red band. NDVI was used to create land cover classes across vegetated and non-vegetated surfaces in cities.

3.3 Calculation of enhanced built-up and bareness index (EBBI)

This study used EBBI to extract built-up features and separate the built-up from the bare surfaces in order to explore the association with LST. The EBBI method uses the MIR, NIR and TIR bands. Higher positive values indicate built-up features and bare surfaces and these two can be distinguished using threshold values. The EBBI can be derived using the following equation[16]:

$$EBBI = \frac{(MIR - NIR)}{10\sqrt{MIR} + TIR} \tag{2}$$

MIR represents reflection in the mid-infrared band (SWIR band 6), NIR represents reflection in the near-infrared band (band 5), and TIR represents reflection in the thermal infrared band (band 11). The output images obtained after performing EBBI were reclassified and subsequently, land use classes such as Built-up, non-built-up and Barren/open surface were extracted.

3.4 Extraction of Land surface temperature (LST)

Land surface temperature is derived using the thermal bands (bands 10 and 11) of Landsat 8 data by following the methods given in the Landsat 8 Data User Handbook[17] and various literature cited along with equations.

3.4.1 Spectral Radiance (Lλ)

LST extraction begins with the conversion of the thermal band's digital number (DN) into spectral radiance using radians scaling factors:

$$L\lambda = ML * DN + AL \tag{3}$$

Where, Lλ is the spectral radiance in $Wm^{-2}sr^{-1}mm^{-1}$. ML and AL are the radiance multiplicative and radiance additive scaling factors from the metadata files of Landsat 8 data. DN is the digital number of pixels.

3.4.2 Brightness temperature (T) conversion

After the conversion to radiance value, the brightness temperature was calculated using the given formula:

$$T = \frac{K2}{ln\left(\frac{K1}{L\lambda}\right) + 1} - 273.15 \tag{4}$$

Where T is the brightness temperature, Lλ is the spectral radiance in $Wm^{-2}sr^{-1}mm^{-1}$; K2 and K1 are band-specific thermal conversion constant obtained from the metadata files. In order to obtain the result in degree Celsius, the absolute zero (approx. $-$ 273.15°C) is added to the above equation of brightness temperature.

3.4.3 Determination of surface emissivity (ε) and LST

Land surface emissivity (ε) governed by land surface characteristics was estimated using the NDVI thresholds method. Afterward, the proportion of vegetation (Pv), of each pixel was determined from the NDVI using the following equation:

$$P_v = \left(\frac{NDVI - NDVI\,min}{NDVI\,max - NDVI\,min}\right)^2 \tag{5}$$

Where P_v is the proportion of vegetation; NDVI is the Normalized Difference Vegetation Index; NDVI min is the minimum NDVI value; NDVI max is the maximum NDVI value.

$$\varepsilon = 0.004 * Pv + 0.986 \tag{6}$$

Thereafter, the surface emissivity was computed using the Equation (6). Where, ε is emissivity, P_v is the proportion of vegetation, 0.004 and 0.986 are the correlation values of surface emissivity. Finally, the LST was derived using the following equation:

$$LST = \frac{T}{1 + (\lambda \sigma T/(hc))\ln \varepsilon} \tag{7}$$

Where, T is brightness temperature; λ is the effective wavelength (thermal bands of Landsat 8 data), the value of σ is 1.38×10^{-23} J/K (i.e., Boltzmann constant), h has the value of 6.626×10^{-34} Js (i.e., Plank's constant), the value of c is 2.998×10^{-8} m/sec (i.e., velocity of light in a vacuum) and ε is emissivity.

3.5 Urban Hot Spot (UHS)

Urban hot spots are created to locate urban areas with higher concentration of LST values. These warm small pockets create unfavourable thermal conditions for human settlement[18]. In this study the LST maps were used to delineate the UHS in two cities using the following equation[19]:

$$\begin{aligned} UHS &= (LST > \mu + 2 * \sigma) \\ Non\,UHS &= (LST < \mu + 2 * \sigma) \end{aligned} \tag{8}$$

Where, UHS is Urban Hot Spot, μ is the mean LST value and σ is the Standard deviation of LST.

3.6 Urban thermal field variance index (UTFVI)

The Urban Thermal Field Variance Index (UTFVI) was derived after computing the LST for the two cities. The UTFVI describes heat island conditions in any given area[20] and has been used as an indicator to measure thermal comfort in cities. The following formula has been used to derive UTFVI:

$$UTFVI = \frac{Ts - Tmean}{Tmean} \tag{9}$$

Where, UTFVI= Urban Thermal Field Variance Index; Ts is the LST (°C); Tmean is the Mean LST (°C).

4 Results and discussion

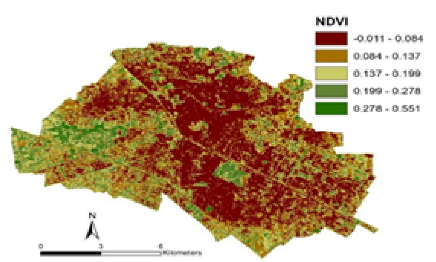
4.1 Distribution of NDVI, EBBI and LST in Ludhiana city

The value of NDVI in Ludhiana city is in the range of -0.01 to 0.55 and the value of EBBI is between -0.66 to 0.63 in the year 2019. NDVI values are higher on agricultural land and other green spaces in the western part of the city (Figure 2**a** and b). Figure 2**c** and **d** show higher EBBI values on fallow agricultural land, barren surfaces on the outskirts of the city and built-up areas in the central part of the city. Three LULC classes (built-up, barren surface and non-built-up) were created from EBBI for Ludhiana city (Figure 2 **c** and **d**). The area derived through indices are given in Table 2.

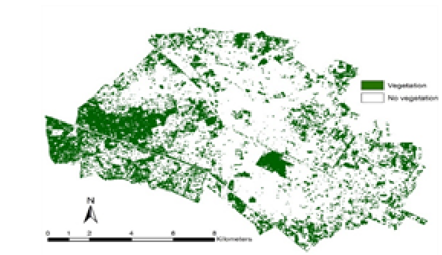
LST value (in °C) of Ludhiana city lies between 24.9 °C and 39.5 °C for May 2019. Figure 2**e** shows the spatial variability of the land surface temperature in the city categorised into six classes. Earlier study conducted on Ludhiana city for the month of September and October reported an increasing trend in the maximum LST value from 35° C in 2009 to 38 °C in 2015. The present study records a further increase in the maximum LST value in May 2019. The reason for this is the availability of sunlight received during a particular month (May-June). Temperatures are very high in the month of May which increase the thermal response of the land surface. LST over densely built-up surfaces was more than 32 °C. The industrial areas recorded more than 37 °C LST during summer season. LST was found to be less than 32 °C in green areas in the city.

Table 2. Geographical area (KM^2) through various indices and LST

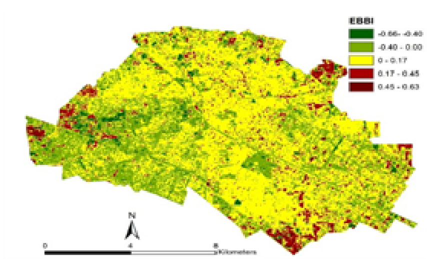
Cities	NDVI		EBBI			LST (°C)			
	Vegetation	No vegetation	Non-built-up	Built-up	Barren open surface	<30	30-34	34-37	>37
Ludhiana	41.57	117.43	55.53	78.38	08.06	40.43	74.21	43.54	0.73
Amritsar	55.85	80.50	51.65	62.41	22.29	56.24	74.22	5.60	0.27



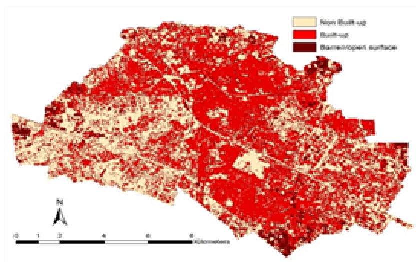
(a) NDVI values across Ludhiana city



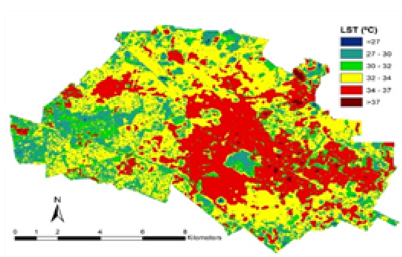
(b) NDVI based Land cover class in Ludhiana city



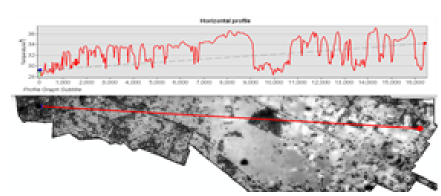
(c) EBBI values across Ludhiana city



(d) EBBI based Land cover classes in Ludhiana city



(e) Land surface temperature map of Ludhiana city

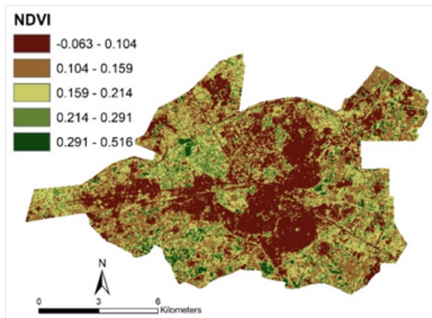


(f) Land surface temperature profile at west east line in central part of Ludhiana city

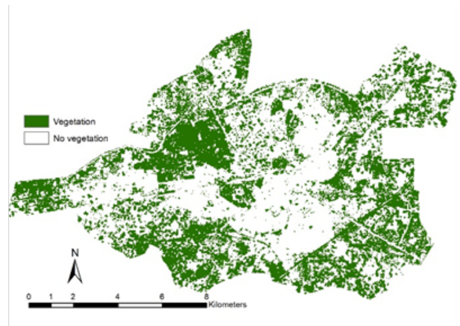
Fig 2. Land surface temperature (LST) and land cover indices in Ludhiana city (May 2019)

4.2 Distribution of NDVI, EBBI and LST in Amritsar city

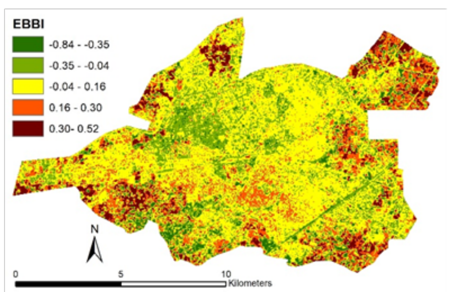
NDVI value in Amritsar city ranges from -0.06 to 0.51 and EBBI value ranges from -0.84 to 0.52 in May, 2019. NDVI values are higher on agricultural land and green spaces in the north-western and southern parts of the city, whereas these values are lower on built-up surfaces (Figure 3**a** and **b**). Three LULC classes (built-up, barren surface and non-built-up) were created from EBBI for Amritsar city (Figure 3 **c** and **d**). The area derived through indices are given in Table 2.



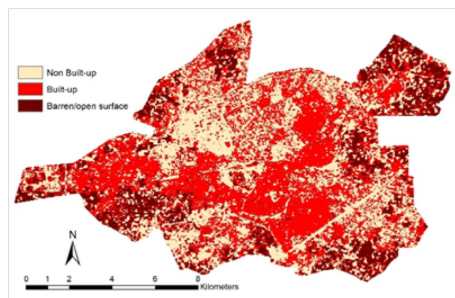
(a) NDVI values across Amritsar city



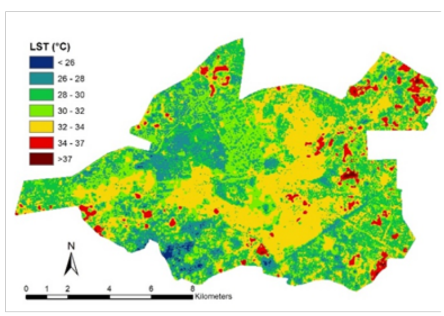
(b) NDVI based Land cover class in Amritsar city



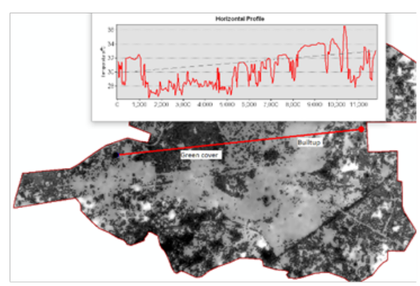
(c) EBBI values across Amritsar city



(d) EBBI based Land cover classes in Amritsar city



(e) Land surface temperature map of Amritsar city



(f) Land temperature profile at west east line in northern Amritsar city

Fig 3. Land surface temperature and land cover indices in Amritsar city (May 2019)

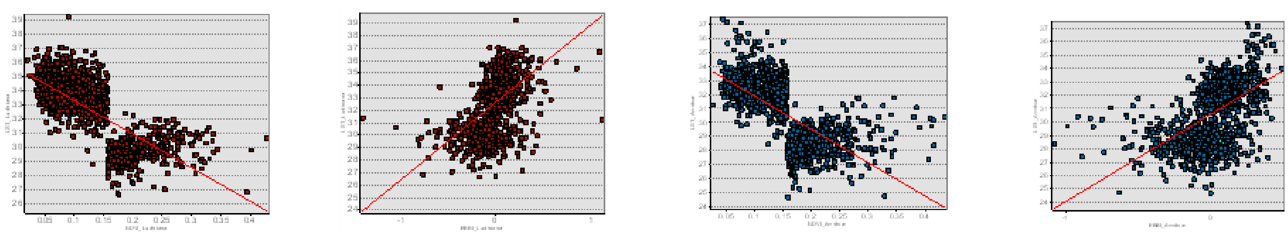
The LST (°C) value of Amritsar city lies between 23.6 °C and 39.3 °C for May 2019. LST values were divided into 7 classes (Figure 3**e**). Higher LST values are observed in the central part of the city corresponding to barren open surface and built-up surface. The north-western part with extensive urban green spaces and the south-western part with standing crops show low surface temperatures. LST on built up surfaces was more than 32 °C and even higher values (more than 35 °C) were recorded on barren/open surfaces and industries during the summer season. On the contrary, the LST was lower (less than 30 °C) over green areas in the city. The west–east horizontal profile (Figure 3 **f**) shows distinct LST patterns on two different surfaces: built-up and urban green spaces. LST is observed to be high along the major roads of the city which are devoid of vegetation.

4.3 Correlation between LST-NDVI and LST-EBBI

To demonstrate the correlation between LST, NDVI and EBBI, over 1200 random ground pixels were drawn in each city. A scatter plot is created to analyse the LST-NDVI and LST-EBBI relationship (Figure 4). LST shows negative correlation with NDVI in both the cities (−0.710, R^2 = 0.505 for Amritsar and -0.754, R^2 = 0.569 for Ludhiana). Higher values of NDVI (indicating vigorous vegetation) correspond to lower values of LST while lower values of NDVI correspond to higher values of LST. The result indicates a cooling effect of vegetation cover on land surface temperatures across both the cities. The correlation between LST and EBBI is found to be positive in both the cities (0.531 for Amritsar and 0.541 for Ludhiana) (Table 3 and Figure 4). Higher values of EBBI indicate the presence of built up and bare surfaces and correspond to higher LST values. On the other hand, lower values of EBBI which denote water bodies and vegetation cover correspond to lower values of LST.

Table 3. Pearson's correlation coefficient values

Cities	LST-NDVI	LST- EBBI
Ludhiana	-0.754	0.531
Amritsar	-0.710	0.541



(a) $R^2 = 0.569$ (b) $R^2 = 0.282$ (c) $R^2 = 0.505$ (d) $R^2 = 0.293$

Fig 4. Scatter plot of LST-NDVI and LST-EBBI of: Ludhiana city (a and b); Amritsar city (c and d). Red line shows the trend line

4.4 Urban hotspots (UHS) detection in cities of Punjab

This section analyses how urban hot spots (UHS) are organized spatially. Table 4 shows the threshold values generated for UHS detection. The threshold value of LST which is UHS compliant, is 35.3 °C and 37.1 °C in the cities of Amritsar and Ludhiana respectively. The results indicate that UHSs are found in industrial areas of the two cities. In Ludhiana city, UHSs were abundant on built-up surfaces (mostly in the industrial area) in the east-central parts, where there is a lack of vegetation cover. The south-eastern parts of the city have a concentration of industries and metal-roofed buildings which favour the development of UHSs (Figure 5 **a**). Therefore, it is not only the built-up area that is causing high UHS formation, but the industries mixed with the built-up surfaces are also jointly influencing the response of LST. On the other hand, UHS are found on built surfaces with metal roofs and brick-kiln sites in the city of Amritsar. Earlier study has reported the contribution of industries in modifying the thermal environment of cities and in creating UHS[21].

Table 4. Threshold values for UHS delineation

	Mean LST °C (μ)	SD (σ)	UHS (LST $> \mu + 2 * \sigma$)	Non UHS (LST $< \mu + 2 * \sigma$)
Ludhiana	32.80	2.15	>37.1	<37.1
Amritsar	30.70	2.30	>35.3	<35.3

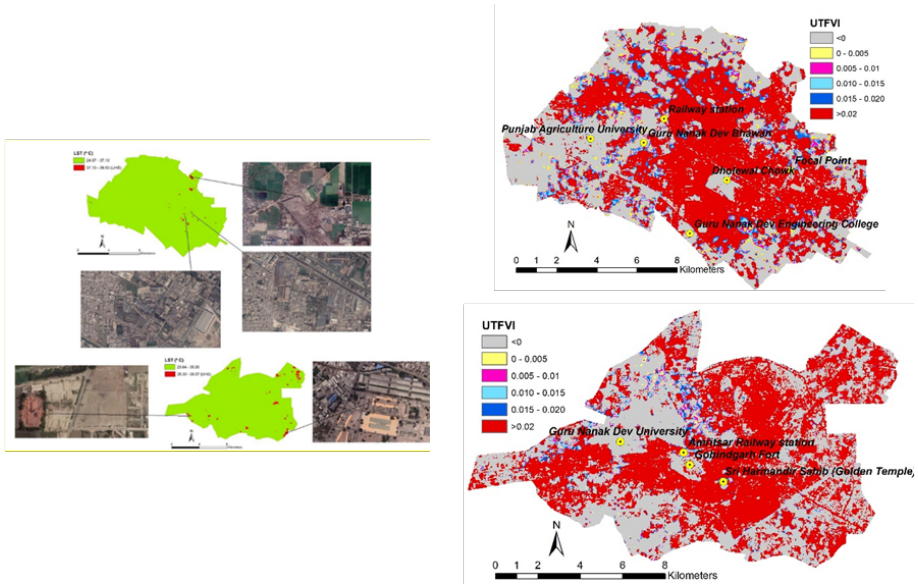


Fig 5. Urban hotspots (UHS) in Ludhiana city and Amritsar city (left); (b) UTFVI of Ludhiana city (top right) and, Amritsar city (bottom right)

4.5 UTFVI based Ecological evaluation in cities of Punjab

UTFVI provides ecological assessment indicators in urban environments through six categories presented in Table 5. A low value of UTFVI indicates good ecological condition while a high value indicates poor ecological condition. Figure 5 **b** shows the Ecological Assessment Index of the cities as per UTFVI. Excellent category (i.e., UTFVI < 0) is observed in places with vegetation/trees/parks and water bodies. In the cities of Ludhiana and Amritsar, this category corresponds to agricultural land and urban green spaces. The study indicates that 45.59 percent of geographical area of Amritsar city has excellent ecological status during the summer months. The Cantonment, Guru Nanak Dev University, Gobindgarh Fort and Maharana Ranjit Singh Udyan (park) located in the north-central part of Amritsar city have a good amount of urban green spaces providing good thermal comfort and improving the overall environmental quality of the city. Unlike the earlier study on Ludhiana city which revealed that more than 50 per cent of the area has excellent ecological status, the present study reports that only 37 per cent of the geographical area has excellent ecological status during the summer month. On the other hand, the worst category (UTFVI > 0.020) is observed on impervious surfaces and industrial areas (mostly built-up/industrial waste areas shown in red) without green cover in both the cities. Bad and worse thermal conditions (i.e., 0.010 < UTFVI < 0.020) are observed around the impervious surfaces with the worst thermal conditions.

Table 5. Threshold values of UTFVI for ecological evaluation

UTFVI	UHI phenomenon	Ecological evaluation index	Percentage of area (%)	
			Ludhiana	Amritsar
<0.000	None	Excellent	36.82	45.59
0.000–0.005	Weak	Good	2.92	1.15
0.005–0.010	Middle	Normal	3.48	1.46
0.010–0.015	Strong	Bad	4.13	1.72
0.015–0.020	Stronger	Worse	4.63	1.97
>0.020	Strongest	Worst	48.02	48.11

5 Conclusion

In this study, thermal comfort and ecological condition in Ludhiana and Amritsar cities have been analysed based on LST and LULC using remote sensing techniques. A summary of the findings is as follows:

1. The UHS output is a function of urban surface properties and both cities are experiencing the UHS phenomenon.
2. Correlation analysis confirmed the significant relationship of LST with NDVI and EBBI. LST has a positive association with EBBI indicating the control of impervious surface on LST. On the other hand, the relationship between LST and NDVI is negative indicating the cooling effect of vegetation and water bodies.
3. The central part of both cities lacks vegetation cover and has more built-up surfaces and, therefore, experiences higher LST.
4. Green spaces are found on the outskirts or in planned areas of cities where LST values are less.
5. Barren/open surfaces in both cities experience comparatively higher LST during summer months.
6. Due to industrial activities, the maximum LST value of summer month was found to be higher in Ludhiana city as compared to Amritsar city. Lack of vegetation cover in residential and industrial areas is worsening thermal comfort in the city.
7. With respect to ecological condition and thermal comfort, Ludhiana city performs worse than Amritsar city. About 47 per cent of geographical areas are exhibiting excellent and good ecological status during the summer months in Amritsar city, while in Ludhiana city it is 40 per cent.

People's well-being largely depends on the environmental quality of cities. Previous literature has confirmed that LST becomes warmer during the summer season and local authorities need to improve their plans according to seasonal variations in LST to improve the urban thermal environment(19). Various strategies and techniques are recommended to tackle thermal imbalance caused by heat in different cities, enhance environmental quality and build adaptive capacities of urban areas. This research strongly recommends expanding green cover and protecting existing green spaces(22).

Acknowledgement

The author is grateful to University of Allahabad, Prayagraj and Central University of Punjab, Bathinda, India for providing infrastructural support. The author is obliged to USGS server (http://earthexplorer.usgs.gov/) for cost free satellite data. The constructive suggestions and feedback of editor and reviewers are duly acknowledged.

References

1) The Strategic Plan 2020-2023. UN Habitat. 2019. Available from: https://unhabitat.org/sites/default/files/documents/2019-09/strategic_plan_2020-2023.pdf.
2) Wei T, Wu J, Chen S. Keeping Track of Greenhouse Gas Emission Reduction Progress and Targets in 167 Cities Worldwide. *Frontiers in Sustainable Cities*. 2021;3:1–13. Available from: https://doi.org/10.3389/frsc.2021.696381.
3) Pramanik S, Punia M. Land use/land cover change and surface urban heat island intensity: source–sink landscape-based study in Delhi, India. *Environment, Development and Sustainability*. 2020;22(8):7331–7356. Available from: https://dx.doi.org/10.1007/s10668-019-00515-0. doi:10.1007/s10668-019-00515-0.
4) Sun Z, Du W, Jiang H, Weng Q, Guo H, Han Y, et al. Global 10-m impervious surface area mapping: A big earth data based extraction and updating approach. *International Journal of Applied Earth Observation and Geoinformation*. 2022;109:1–16. Available from: https://dx.doi.org/10.1016/j.jag.2022.102800. doi:10.1016/j.jag.2022.102800.
5) Dewan A, Kiselev G, Botje D. Diurnal and seasonal trends and associated determinants of surface urban heat islands in large Bangladesh cities. *Applied Geography*. 2021;135:1–11. Available from: https://dx.doi.org/10.1016/j.apgeog.2021.102533. doi:10.1016/j.apgeog.2021.102533.
6) Jibitha JB, Achu AL, Joseph S, Prasood SP, Thomas J, Selvakumar S. Assessment of changes in land use/land cover and land surface temperature in a fast-growing urban agglomeration of Southern India. *Environment, Development and Sustainability*. 2024. Available from: https://dx.doi.org/10.1007/s10668-024-04494-9. doi:10.1007/s10668-024-04494-9.
7) Naim MNH, Kafy AA. Assessment of urban thermal field variance index and defining the relationship between land cover and surface temperature in Chattogram city: A remote sensing and statistical approach. *Environmental Challenges*. 2021;4:1–14. Available from: https://dx.doi.org/10.1016/j.envc.2021.100107. doi:10.1016/j.envc.2021.100107.
8) Vuckovic M, Schmidt J, Ortner T, Cornel D. Combining 2D and 3D Visualization with Visual Analytics in the Environmental Domain. *Information*. 2022;13(1):1–21. Available from: https://dx.doi.org/10.3390/info13010007. doi:10.3390/info13010007.
9) Guha S, Govil H, Diwan P. Analytical study of seasonal variability in land surface temperature with normalized difference vegetation index, normalized difference water index, normalized difference built-up index, and normalized multiband drought index. *Journal of Applied Remote Sensing*. 2019;13(2):1–17. Available from: https://doi.org/10.1117/1.JRS.13.024518.
10) Sahana M, Dutta S, Sajjad H. Assessing land transformation and its relation with land surface temperature in Mumbai city, India using geospatial techniques. *International Journal of Urban Sciences*. 2019;23(2):205–225. Available from: https://dx.doi.org/10.1080/12265934.2018.1488604. doi:10.1080/12265934.2018.1488604.

11) Singh R, Kalota D. Urban Sprawl and Its Impact on Generation of Urban Heat Island: A Case Study of Ludhiana City. *Journal of the Indian Society of Remote Sensing*. 2019;47:1567–1576. Available from: https://dx.doi.org/10.1007/s12524-019-00994-8. doi:10.1007/s12524-019-00994-8.
12) Majumder A, Setia R, Kingra PK, Sembhi H, Singh SP, Pateriya B. Estimation of land surface temperature using different retrieval methods for studying the spatiotemporal variations of surface urban heat and cold islands in Indian Punjab. *Environment, Development and Sustainability*. 2021;23(11):15921–15942. Available from: https://dx.doi.org/10.1007/s10668-021-01321-3. doi:10.1007/s10668-021-01321-3.
13) Srikanth K, Swain D. Urbanization and Land surface temperature changes over Hyderabad, a semi-arid mega city in India. *Remote Sensing Applications: Society and Environment*. 2022;28:100858. Available from: https://dx.doi.org/10.1016/j.rsase.2022.100858. doi:10.1016/j.rsase.2022.100858.
14) Venter ZS, Chakraborty T, Lee X. Crowdsourced air temperatures contrast satellite measures of the urban heat island and its mechanisms. *Science Advances*. 2021;7(22):1–9. Available from: https://dx.doi.org/10.1126/sciadv.abb9569. doi:10.1126/sciadv.abb9569.
15) Qadri SMT, Hamdan A, Raj V, Ehsan M, Shamsuddin N, Hakimi MH, et al. Assessment of Land Surface Temperature from the Indian Cities of Ranchi and Dhanbad during COVID-19 Lockdown: Implications on the Urban Climatology. *Sustainability*. 2023;15(17):1–23. Available from: https://dx.doi.org/10.3390/su151712961. doi:10.3390/su151712961.
16) As-syakur AR, Adnyana IWS, Arthana IW, Nuarsa IW. Enhanced Built-Up and Bareness Index (EBBI) for Mapping Built-Up and Bare Land in an Urban Area. *Remote Sensing*. 2012;4(10):2957–2970. Available from: https://dx.doi.org/10.3390/rs4102957. doi:10.3390/rs4102957.
17) Landsat 8 (L8) Data Users Handbook. Version 5.0 ed. USGS. 2019. Available from: https://docslib.org/doc/9616300/landsat-8-l8-data-users-handbook.
18) Guha S, Govil H, Dey A, Gill N. Analytical study of land surface temperature with NDVI and NDBI using Landsat 8 OLI and TIRS data in Florence and Naples city, Italy. *European Journal of Remote Sensing*. 2018;51(1):667–678. Available from: https://dx.doi.org/10.1080/22797254.2018.1474494. doi:10.1080/22797254.2018.1474494.
19) Saha J, Ria SS, Sultana J, Shima UA, Seyam MMH, Rahman MM. Assessing seasonal dynamics of land surface temperature (LST) and land use land cover (LULC) in Bhairab, Kishoreganj, Bangladesh: A geospatial analysis from 2008 to 2023. *Case Studies in Chemical and Environmental Engineering*. 2024;9:1–12. Available from: https://dx.doi.org/10.1016/j.cscee.2023.100560. doi:10.1016/j.cscee.2023.100560.
20) Kafy AA, Abdullah-Al-Faisal, Rahman MS, Islam M, Rakib AA, Islam MA, et al. Prediction of seasonal urban thermal field variance index using machine learning algorithms in Cumilla, Bangladesh. *Sustainable Cities and Society*. 2021;64:102542. Available from: https://dx.doi.org/10.1016/j.scs.2020.102542. doi:10.1016/j.scs.2020.102542.
21) Portela CI, Massi KG, Rodrigues T, Alcântara E. Impact of urban and industrial features on land surface temperature: Evidences from satellite thermal indices. *Sustainable Cities and Society*. 2020;56:102100. Available from: https://dx.doi.org/10.1016/j.scs.2020.102100. doi:10.1016/j.scs.2020.102100.
22) Basu T, Das A. Urbanization induced degradation of urban green space and its association to the land surface temperature in a medium-class city in India. *Sustainable Cities and Society*. 2023;90:104373. Available from: https://dx.doi.org/10.1016/j.scs.2022.104373. doi:10.1016/j.scs.2022.104373.